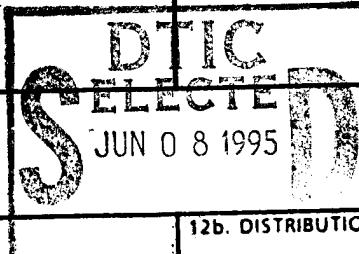


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<p>IN THE PORTION OF THIS PROJECT FUNDED BY BMDO/IST, WE HAVE BEEN DEVELOPING THE ELEMENTS OF A DIAMOND BASED SEMICONDUCTOR TECHNOLOGY FOR HIGH TEMPERATURE APPLICATIONS. THE APPROACH IS CENTERED AROUND INCORPORATING A SCHOTTKY BARRIER CONTACT AND MOS FIELD-EFFECT TRANSISTOR USING DIAMOND FILMS PREPARED BY MICROWAVE PLASMA CHEMICAL VAPOR DEPOSITION (MPACVD). THE EXPERIMENTAL BASIS FOR THIS RESEARCH IS THE SUCCESSFUL FABRICATION IN OUR LABORATORY OF THE WORLD'S FIRST SCHOTTKY DIODES WITH PACVD DIAMOND BASE. THESE DEVICES HAVE CHARACTERISTICS SIMILAR TO THEIR COUNTERPARTS FABRICATED USING SINGLE CRYSTAL SYNTHETIC DIAMOND PREPARED BY HIGH PRESSURE METHODS. THIS HAS REQUIRED A DETAILED UNDERSTANDING AND CONTROL OF THE DEPOSITION PROCESS AS IT RELATES TO THE CHEMICAL PURITY AND STRUCTURAL PERFECTION OF THE RESULTING SINGLE CRYSTAL DIAMOND FILMS. IN ADDITION, DETAILED CHARACTERIZATION OF THE FILMS HAS ALLOWED FOR MEANINGFUL PREPARATION-CHARACTERIZATION-ELECTRONIC PROPERTY RELATIONS. THE ULTIMATE GOAL OF THE PROPOSED RESEARCH IS TO FABRICATE TRANSISTORS ON SINGLE CRYSTAL HETEROEPITAXIAL DIAMOND AND TO FABRICATE SMALL SCALE INTEGRATED CIRCUIT OPERATIONAL AT 400-500°C.</p>			
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A. Badzian and T. Badzian, "Routes to Diamond Homoepitaxy" Mat. Res. Soc. Symp. Proc.  
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N. Lee and A. Badzian "Effect of misorientation angles on the surface morfologies of (001) homoepitaxial diamond thin films" Applied Physics Letters, 66, 2203-2205, 1995

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**PRESENTATIONS**  
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A. Badzian and T. Badzian "Interfaces in Diamond Nucleation Processes" International Conference on Metallurgical Coatings and Thin Films, April 6-10, 1992, San Diego, CA (symposium chairman)

A. Badzian "Overview of CVD Diamond Deposition" American Vacuum Society New England Chapter, 1992 Annual Symposium - May 18-19, 1992 Burlington ,Ma. (invited talk)

A. Badzian and T. Badzian "Heteroepitaxy of Diamond on Cubic Boron Nitride" Gordon Research Conference, Diamond Synthesis, June 15-19, 1992, Plymouth, NH (poster presentation)

G.P. Lamaze, R.G. Downing, L. Pilione, A. Badzian and T. Badzian "Analysis of Boron in CVD Diamond Surfaces Using Neutron Depth Profiling" 6-th International Conference on Solid Films and Surfaces, Paris France, June 29 - July 3,1992

A. Badzian and T. Badzian "Diamond Homoepitaxy" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany , August 31 - September 4, 1992 /oral presentation, cBN session chairman /

B.G. Yacobi, J. Leibens, K.J. Vahala, A.R. Badzian, and T. Badzian "Preferential Incorcorporation of Defects in Monocrystalline Diamond Films" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany , August 31 - September 4, 1992

G.Sh. Gildenblat, S.A. Grot, A.R. Badzian "Diamond Electronic Devices - State of Art" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany , August 31 - September 4, 1992 /invited talk/

A. Badzian "Issues on Diamond Syntesis, Crystal Structure and Properties" invited talk at Nishi Tokyo University, Tokyo, Japan , December 1992

A. Badzian "Synthesis and Crystal Structure of Boron - Carbon - Nitrogen Phases" invited talk at National Institute in Research in Inorganic Materials, Tsukuba, Japan, December 1992

A. Badzian and T. Badzian "High Temperature Limit for CVD Diamond Growth" International Conference on Metallurgical Coatings and Thin Films, San Diego, CA, April 19-23,1993

A. Badzian "Progress Report on Project: Transistor on Heteroepitaxial Diamond" Combined DARPA / SDIO / ONR Diamond Program Review, Arlington, Virginia, 27-30 April,1993

A. Badzian, T.Badzian and S.-Tong Lee "Synthesis of Diamond from Methane and Nitrogen Mixture" 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

A. Badzian and T.Badzian "High Temperature Epitaxy of Diamond" 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

A. Badzian and T. Badzian "Nickel Hydride Assistance in CVD Diamond Growth" 183rd Meeting

of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

R. Roy and A. Badzian "Nontraditional Approaches to Diamond Synthesis" The 3rd IUMRS (International Union of Materials Research Societies) International Conference on Advanced Materials, Sunshine City, Ikebukuro, Tokyo, Japan, August 31 - September 4, 1993 /invited talk/

A. Badzian "Issues on Epitaxial Growth of Diamond " NIRIM International Symposium on Advanced Materials '94, Tsukuba, Japan, March 13-17, 1994 (invited talk)

A. Badzian "Diamond Nucleation and Epitaxy" 1994 March Meeting of the American Physical Society, Pittsburgh, Pa, 21-25 March 1994, /invited talk, session chairman/

A. Badzian and T. Badzian "Nucleation of Diamond in Metal-Carbon-Hydrogen Environment" International Conference on Metallurgical Coatings and Thin Films, April 25-29, 1994, San Diego, Ca / session chairman /

A. Badzian "Diamond Epitaxy" Second International Symposium on Diamond Films 3-5 May 1994, Minsk, Belarus / invited; member of Program Committee /

A. Badzian , T Badzian "Defects of CVD Diamonds", 8th CIMTEC Forum on New Materials , Florence, Italy, June28-July 4,1994 / invited, session chairman/

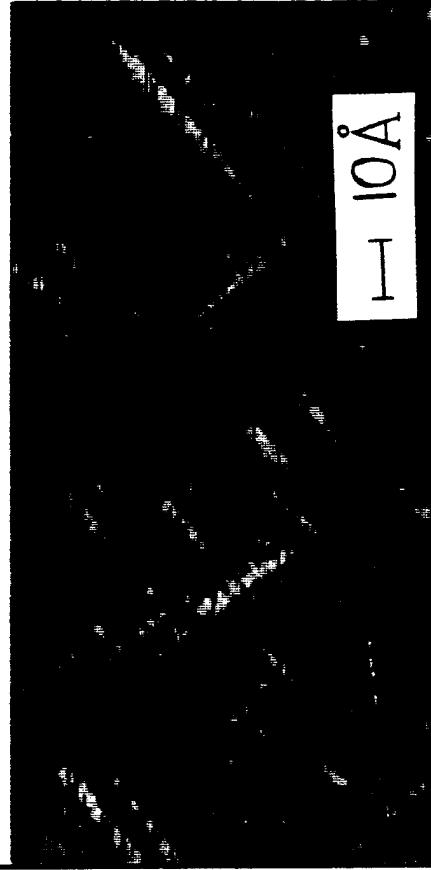
A. Badzian , "Diamond Homoepitaxy", The 4-th International Conference on the New Diamond Science and Technology ICNDST-4, July 18-22, 94, Kobe , Japan / invited; member of Program Committee /

A. Badzian and R. Roy, "Diamond Films: State of Science and Technology" AFOSR/URI Carbon/Carbon Composites Conference and the Carbon Research Centre Symposium, University Park, PA, September 13-14, 1994

# DEVELOPMENT OF THIN FILM DIAMOND BASED INTEGRATED CIRCUIT TECHNOLOGY

P.I.: A. Badzian and G. Sh. Gildenblat  
The Pennsylvania State University

## STM image of reconstructed (001) surface of boron doped diamond homoepitaxial film



## Contract Objective

- \* To fabricate diamond transistor on single crystal heteroepitaxial diamond
- \* To fabricate small-scale IC operational at 400-500°C
- \* To obtain electronic grade diamond films on diamond and non-diamond substrates

## Approach

- \* Microwave plasma assisted chemical vapor deposition synthesis of diamond films and crystals
- \* Experimental studies of growth mechanisms and doping
- \* Experiments on heteroepitaxy on cBN, Ni on Cu, Si and SiC
- \* Develop technological steps to fabricate diamond-based devices
- \* Demonstrate feasibility of high temperature operation of thin film diamond devices

## Progress

- \* Demonstrated heteroepitaxy of diamond on cBN over the area of 250  $\mu\text{m}$ .
- \* Demonstrated nearly perfect diamond films with characteristics of type IIa natural diamond
- \* Nucleation of diamond on Ni and suppression of graphite nucleation
- \* High temperature ( $>1200^\circ\text{C}$ ) growth of high quality diamond films on (001) and 1.2 mm single crystal on (110)
- \* Developed ECR etching method with no substrate bias
- \* Fabricated several recessed-gate MOSFETs using ECR etching process. Devices are operational in the 300-650K temperature range
- \* Developed analytical model of long channel diamond MOSFET

# SINGLE CRYSTAL DIAMOND

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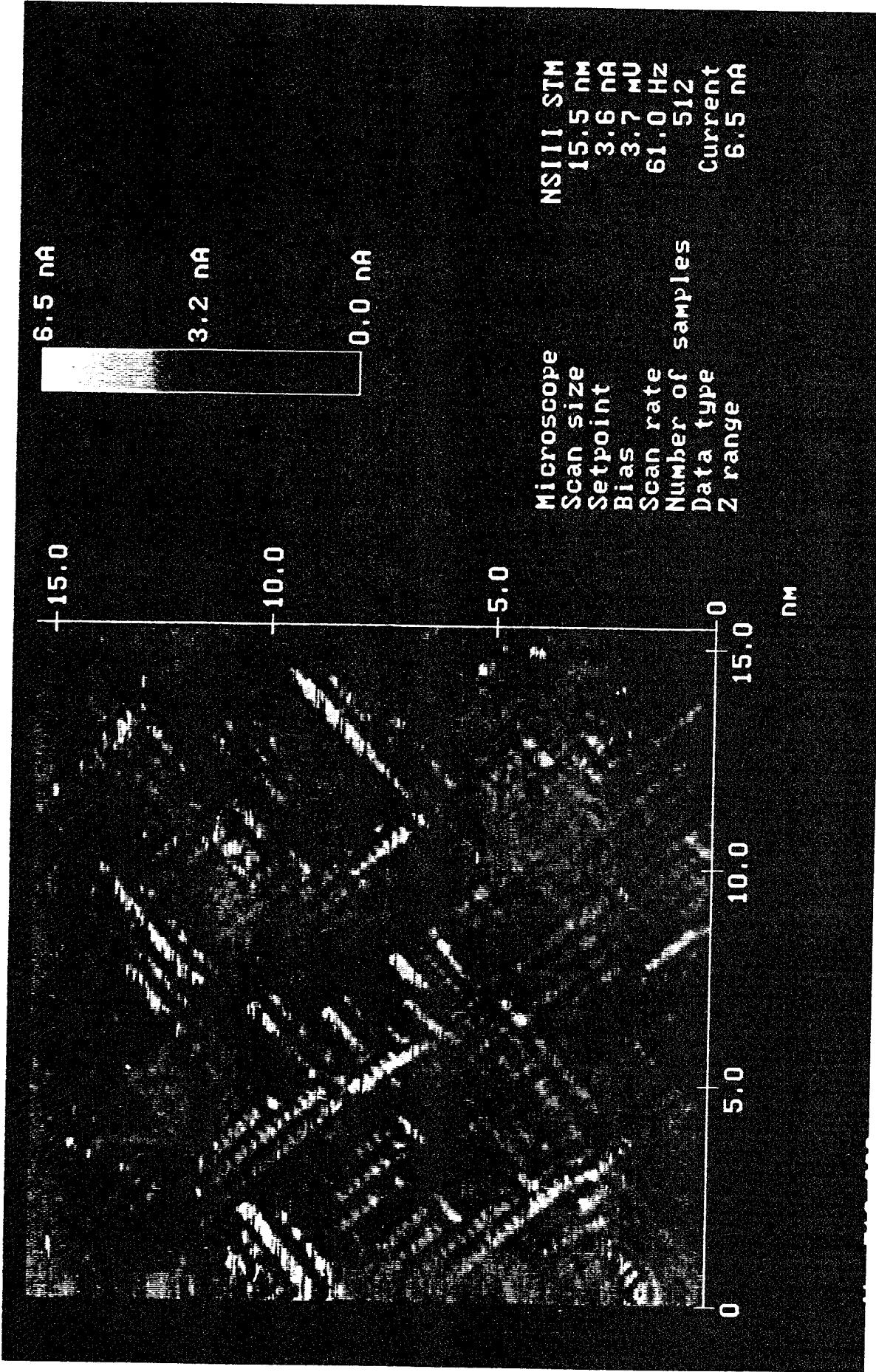
- \* Single crystal growth without secondary nucleation has been demonstrated for (110) epitaxy
- \* No secondary nucleation disturbing expitaxy was observed over the area of diamond substrate 4x4mm
- \* Gem quality crystals have been grown
- \* The films are transparent
- \* The bulk crystal grown during three weeks has a height of 1.2mm

# ELECTRONIC QUALITY CVD DIAMOND FILMS

Electronic films were grown on (001) substrates and the following studies were conducted:

- \* Parametric studies
- \* Role of substrate misorientation (off angle cut)
- \* Lattice defects by Reflection High Energy Electron Diffraction (RHEED) and Scanning TMicroscopy (STM)
- \* Oxygen plasma treatment of diamond surface prior to Schottky diodes fabrication
- \* Control over rectifying contacts is expected to be reached when density of lattice defects will be decreased

STM IMAGE of HYDROGENATED (001) SURFACE of BORON DOPED  
CVD DIAMOND FILM



DIAMERS IMAGE, AREA 15.5 X 15.5 nm

CVD by A. BADZIAN and T. BADZIAN  
STM by Y. KUANG and T.T. TSONG

**SURFACE MORPHOLOGIES OF  
HOMOEPITAXIAL (001) DIAMOND FILMS  
WITH MISORIENTATION ANGLES**

**a**

**b**

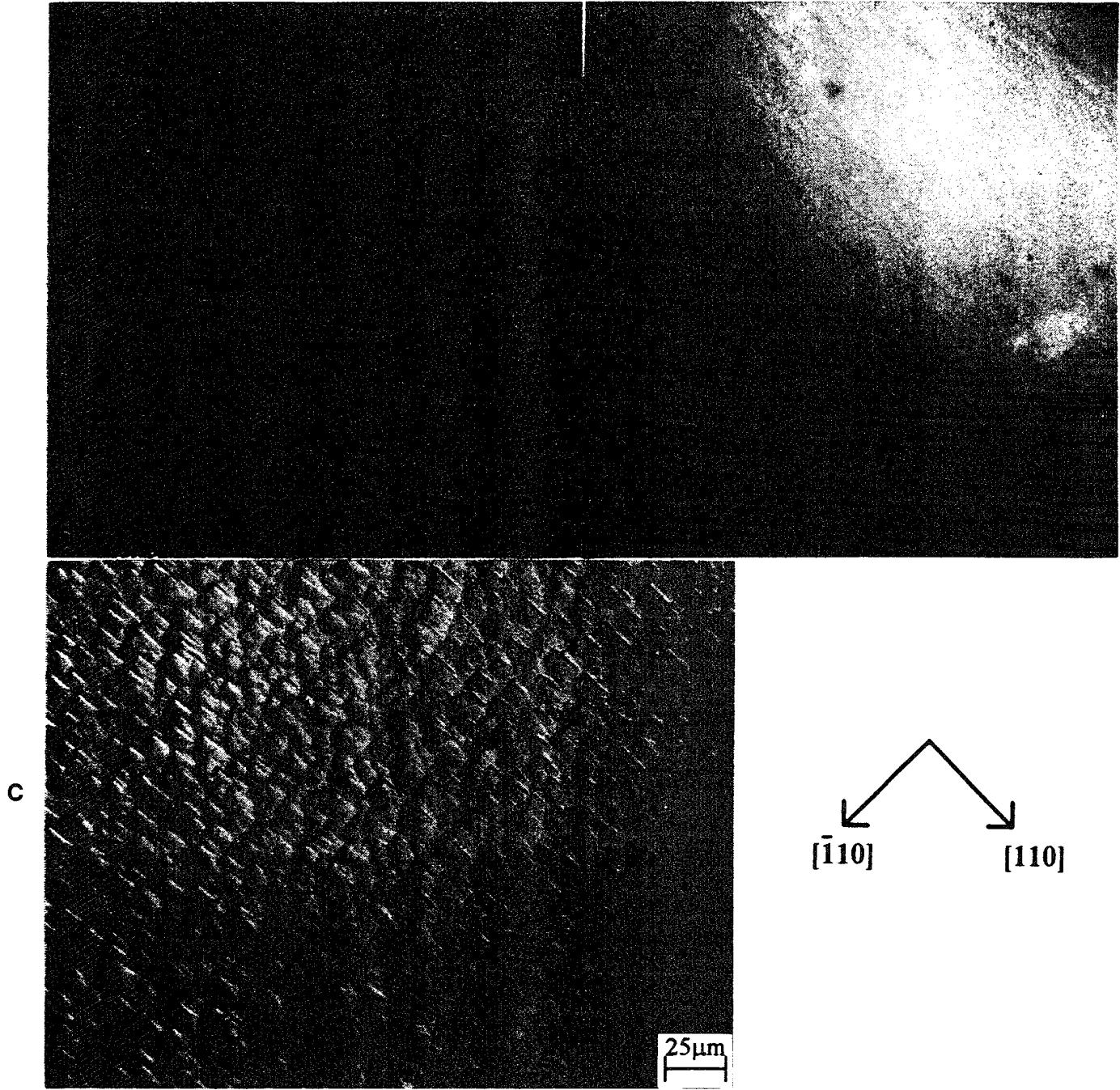


Fig. 2. DICM images of the surface morphologies of epitaxial diamond films grown on (a)  $0.1^\circ$ , (b)  $3.5^\circ$ , and (c)  $11.0^\circ$  off (001) substrates at  $1200^\circ\text{C}$ , 90 torr and 1 %  $\text{CH}_4$  in  $\text{H}_2$  for 5 hrs in (a) and 8 hrs in (b) and (c).

## RHEED OF HOMOEPITAXIAL (001) DIAMOND FILMS

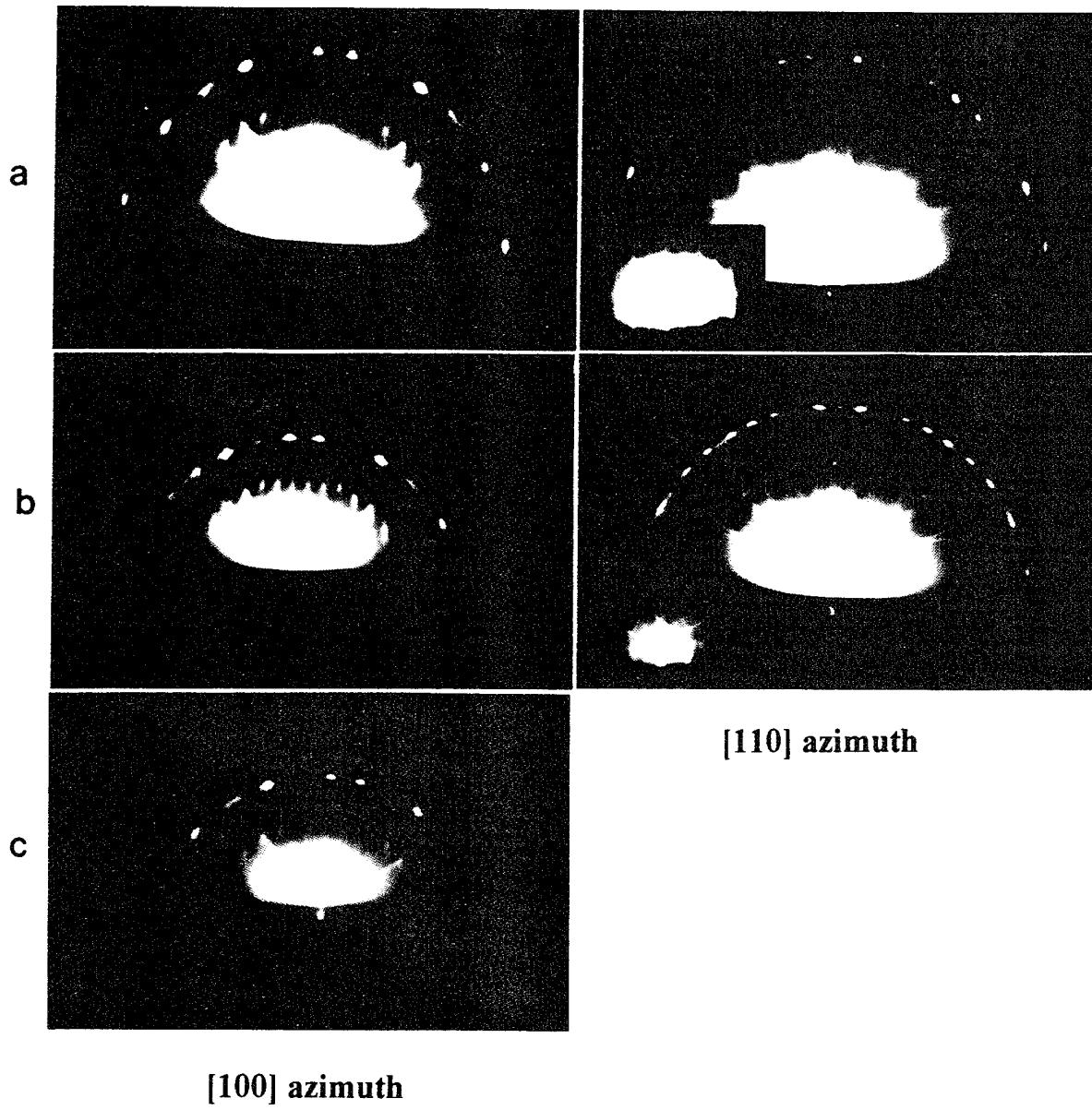


Fig. 3. RHEED patterns of the (001) film surfaces grown on (a)  $0.1^\circ$ , (b)  $3.5^\circ$ , and (c)  $11.0^\circ$  off substrates at the condition specified in Fig. 2, taken from [100] for the left and [110] azimuthal patterns for the right patterns at 40 kV. The insets of [110] azimuthal patterns show magnified views of the zeroth Laue zone.

## **CONCLUSIONS**

- 1 On the well-oriented (001) diamond substrate, growth hillocks are formed by two-dimensional nucleation and lateral migration of the newly created steps due to the lack of surface steps. On the other hand, the growth on the misoriented surface proceeds via step flow along the  $<110>$  directions.
- 2 The growth on the  $3.5^\circ$  off substrate produced the smoothest surface from the surface roughness measurement.
- 3 RHEED showed that the films are single crystals and that their surfaces are composed of a two-domain  $2\times 1$  reconstructed structure. RHEED also indicated that the  $3.5^\circ$  off film surface is the smoothest.